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ABSTRACT

BBN has developed, tested, and fielded pre-production versions of a versatile acoustics-based counter-sniper system. This system was developed by BBN for the DARPA Tactical Technology Office to provide a low cost and accurate sniper detection and localization system. The system uses observations of the shock wave from supersonic bullets to estimate the bullet trajectory, Mach number, and caliber. If muzzle blast observations are also available from unsilenced weapons, the exact sniper location along the trajectory is also estimated. A newly developed and very accurate model of the bullet ballistics and acoustic radiation is used which includes bullet deceleration. This allows the use of very flexible acoustic sensor types and placements, since the system can model the bullet's flight, and hence the acoustic observations, over a wide area very accurately. System sensor configurations can be as simple as two small four element tetrahedral microphone arrays on either side of the area to be protected, or six omnidirectional microphones spread over the area to be monitored. Increased performance can be obtained by expanding the sensor field in size or density, and the system software is easily reconfigured to accommodate this at deployment time. Sensor Nodes can be added using wireless network telemetry or hardwired cables to the Command Node processing and display computer. The system has been field tested in three government sponsored tests in both rural and simulated urban environments at the Camp Pendleton MOUT facility. Performance was characterized during these tests for various shot geometries and bullet speeds and calibers.

Keywords: sniper, gunfire, acoustic, shock wave

1. INTRODUCTION

A flexible, accurate, and inexpensive acoustic sniper detection and localization system has been developed at BBN under DARPA funding. At its core, the system contains a detailed parametric model of the shock wave and muzzle blast space-time waveforms. Using this, observations of the shock wave and/or muzzle blast on two or more small tetrahedral microphone arrays, or six or more distributed omnidirectional microphones are inverted for the bullet trajectory, speed, and caliber. If the muzzle blast is available, the shooter 3-coordinate location is also estimated. Both amplitude and spectral characteristics as well as travel-time measurements are extracted from the acoustic data to globally estimate the unknown parameters using robust modeling techniques.

A ruggedized fieldable prototype system was developed and tested in real-time with live-fire tests. This system uses a PC-104 based Command Node hosting the detailed detection, classification, and localization algorithms, as well as the graphical user interface. Acoustic data from the microphones are digitized either directly by the Command Node for a "hard-wired" system, or by environmentally protected PC-based Data Nodes communicating with the Command Node over an RF network for the wireless version. Small size, battery power, and GPS-based time synchronization of these Data Nodes allows the sensors to be arbitrarily distributed and optimized for acoustic accuracy and coverage. While the system will operate with as few as two directional acoustic nodes, barrier-type coverage and increased reliability and accuracy can be obtained with additional Data Nodes and microphones. Both the localization algorithms and software, and the RF network communications architecture allow reconfiguration for more acoustic sensors, either omni or directional. The algorithms automatically adapt to handle the total available sensor field, as well as the particular set of microphones which have detectable signals on any given shot. Results are displayed in both numerical form, and as an overlay on a digital map display.

We describe the results from government testing with hundreds of accurately known shots in both open and urban environments. Key to system performance is a supersonic projectile trajectory model derived from physical principles. Results show this model to be in closer agreement with experimental data than existing empirical trajectory models.

The paper is organized in the following manner. We first present the system concepts under which the design was undertaken, and their rationale. We then describe the system architecture for obtaining the desired functionality. This is followed by a brief discussion of the bullet ballistics model used. Finally, we discuss the system use and performance during government sponsored and directed blind testing.

2. SYSTEM CONCEPTS

The BBN counter-sniper system development was guided by three primary goals:

- High-accuracy estimation of both bullet trajectory and shooter location.
- Ease of reconfiguration to handle different threat and system deployment scenarios.
- Implementation using robust and inexpensive sensors and processing.

Each of these and their system concept implications are discussed in the following sections.

2.1 Goal 1: High-accuracy estimation of bullet trajectory and shooter location

High accuracy is required in a counter-sniper system because the threat must be localized for both self protection and response. Our goal was to obtain window-sized localization at several hundred meters range to the shooter. Because the muzzle blast and flash can be easily countermeasured, observables from the actual flight of the supersonic bullet must be used. A characteristic and unavoidable signature of such bullets is the acoustic shock wave emitted from all points along its trajectory, leading naturally to our choice of an acoustic sensing technique. If the bullet trajectory is estimated, it can then be followed back to the shooter. While observations of the shock alone do not uniquely locate the shooter along this trajectory, prior information on the muzzle speed of the bullet, or the intersection of the trajectory with known topographic or man-made features provide relatively unambiguous shooter locations. Additionally, if the acoustic muzzle blast signature is also observed, a very high quality estimate of the shooter location can be obtained using the time of arrival difference between the shock and muzzle waves.

Initial modeling of the estimation performance of various sensor geometries, from dense compact arrays to widely distributed omni microphones, led us to the conclusion that a distributed sensor concept would provide the highest performance with practical sensor tolerances and costs. In particular, a system with microphones on either side of a trajectory greatly decreases the ambiguity between the Mach cone angle and the trajectory angles. This vastly improves accuracy and reduces system tolerance requirements by not requiring wavefront curvature to be observed across a small aperture to resolve the ambiguity. However, because the Mach angle changes as the bullet slows, an accurate ballistics model including bullet deceleration is required to model and integrate the data over a distributed area for trajectory parameter estimation. These issues are illustrated in Figure 1.

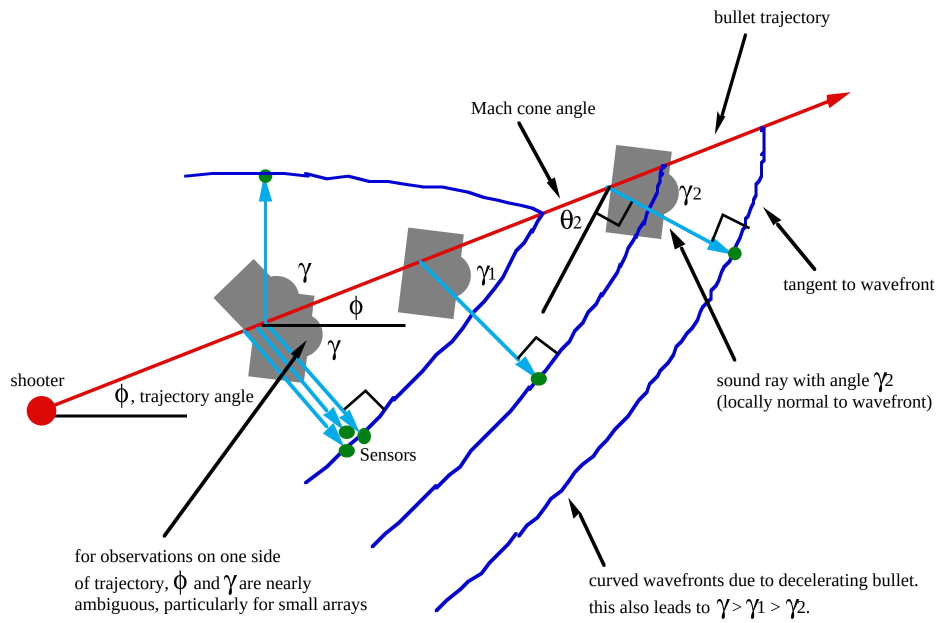

Figure 1. Key trajectory ballistics and shock wave characteristics for distributed sensor concepts.

Thus the first goal leads to the first three system concepts:

1) Use of the acoustic shock wave as the primary observable.
2) Need for an accurate trajectory ballistics and shock acoustical model applicable over the entire bullet trajectory. This will be used in an inversion, or estimation, of the model parameters from the observed acoustic shock data observed over a large spatial area.
3) Use of the acoustic muzzle blast when available to unambiguously estimate the shooter position along the trajectory.

2.2 Goal 2: Ease of reconfiguration to handle different threat and system deployment scenarios

A versatile counter-sniper system should be applicable to multiple scenarios, including:

- Area Protection: e.g. determination of the direction of incoming fire on a compound.
- Area Monitoring: e.g. determination of the exact source of fire from a building.
- Point Protection: e.g. protection of a stage or podium area.
- Convoy protection: e.g. protection of a motorcade or convoy.
- Small unit operations: e.g. rapid determination of source of fire on a small moving group.
- Individual operation: e.g. a single soldier or law enforcement officer or vehicle.

The first two are best served by fixed distributed sensors in or around the area to be protected or monitored. This is illustrated in Figure 2. In this type of deployment, either single microphone (omnidirectional) sensors or small arrays may be used. Single microphones are more easily concealed, but require occupation of more points, with increased infrastructural demands for either local power for RF links or for communications and power cables. Alternatively, a lower density of small arrays may be used if their size and visibility are not a limitation. For point protection, two arrays flanking the protected area are ideal. These may be permanent or temporary, and their locations can be determined by a survey at time of installation.

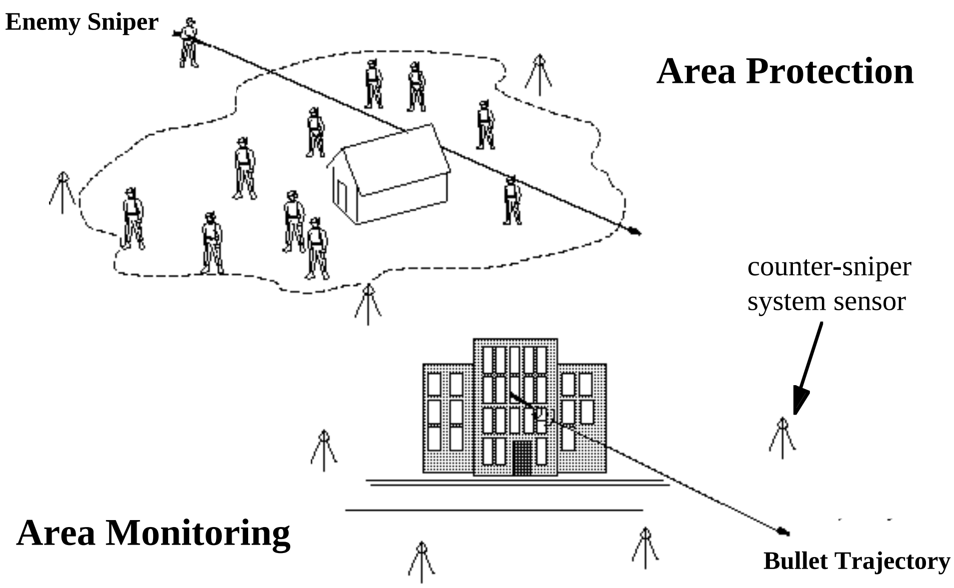

Figure 2. Deployment scenarios for a fixed-sensor counter-sniper system.

Moving convoy protection requires sensors to be mounted on the moving vehicles. This scenario requires that wind noise abatement be applied to the sensors, but the high acoustic level and broadband characteristics of the shock wave make this and engine noise a minimal problem. As long as two or more vehicles are available, the distributed array concept works well. Reasonable precision relative location (such as that available from real-time differential GPS) is adequate for sensor location. Array sensor orientation using commercially available magnetometers and level sensors is problematic on vehicles because of their high accelerations on rough roads, but omni sensors on a large number of vehicles avoids this problem. Alternatively, a strapdown ring laser gyro can be used, although this adds significantly to the cost. It is also possible to use larger surface-mounted arrays for single-vehicle solutions in the vehicle coordinate frame, though the noise problems increase and vehicle shadowing of the acoustic waves is potentially a problem.

Finally, small unit and individual soldier operations pose a unique opportunity for an acoustic sniper system because of the ruggedness, low cost, and low volume and power requirements of the acoustic solution. If six or more soldiers operate in close proximity (e.g. within a 200m radius) individual omni microphones on their helmets with data shared among them by RF communications, and localized by differential GPS (or equivalent) would provide adequate performance. Helmet omni sensors are also attractive in that they do not require orientation sensors to determine the array's attitude. However, this operational scenario seems overly restrictive. To get around this, the helmet can be used as a platform for a flush mounted multi-microphone array. Our current efforts have shown that this is adequate for both accurate distributed localization using shared data from two or more such helmets (supported by GPS and head orientation sensors), and for a lower quality single-helmet solution using shock and muzzle observations.

Thus we conclude that a reconfigurable distributed multi-sensor system is appropriate for many potential applications of a counter-sniper system, and focus on it rather than a large dense single array solution. This is also consistent with our judgment of the maximum performance/cost solution discussed in 2.1. The system concept elements that derive from this are:

4) The use of spatially distributed omni or array acoustic sensors. Array sensors are particularly applicable to some applications, particularly for small area coverage with only two sites, and in man-wearable systems where degraded-mode performance with one system is desirable in case of communications breakdown or GPS failure or blockage.
5) Linkage of these sensors via wireless RF networking for sharing sensor location, orientation, and status information as well as raw data, partially processed data and/or solutions. Hardwire links are also appropriate in some applications.
6) The use of distributed computation, particularly in man-wearable configurations. Each helmeted individual would process his own data together with that transmitted from other individuals to develop a distributed solution. This would avoid single points of failure.

All three of these system concepts are consistent with the first three derived from performance considerations. Acoustic data is fundamentally low rate, and can be processed inexpensively. This allows low-power data reduction at the sensor site which allows very low data rate communications among system elements.

2.3 Goal 3: Implementation using robust and inexpensive sensors and processing

Although the shock wave of a supersonic bullet is quite wide bandwidth near its origin, it gradually loses high frequency content due to acoustic propagation losses. Acoustic counter-sniper systems using solitary compact arrays must effectively use this high-frequency information to obtain the precision inter-sensor time delays needed to resolve wavefront curvature over a small aperture for simultaneous estimation of trajectory and bullet speed. Not only does this potentially reduce the effective area of coverage per microphone of the systems, but this high precision also requires extremely accurately placed and calibrated microphones and broadband data acquisition channels. The high data rates from these require powerful processing to reduce. All of these increase the cost of the system.

For a spatially distributed system, the timing and sensor localization requirements for each microphone are dramatically reduced because of the long acoustic baselines and the better conditioning of the inversion problem using observations on each side of a trajectory. Even for the array subsystems, only relative travel times adequate for the equivalent of reasonably accurate "plane-wave" direction of propagation estimation are required (although the processing is not done that way.) Thus, the bandwidth, calibration, and signal to noise ratio requirements of each microphone are much reduced, and the area covered by each microphone is increased. This leads to fewer and cheaper sensors, electronics, and lower data rate signal processing. Low bandwidth also has the advantage of reduced power consumption at all levels. We have found that more than adequate muzzle and shock arrival time estimates are obtainable with less than 8 kHz bandwidth (20 kHz sampling). This bandwidth is also adequate to support accurate bullet caliber classification using the details of the shock's N-wave. This classification is used for estimation of the bullet ballistic coefficient, which is used in the detailed trajectory modeling supporting the distributed sensor concept. Finally, the use of low-frequency microphones for the shock wave also allows them to be used for the muzzle blast and for future use in distributed mortar and artillery location systems as well. This maintains hardware simplicity, while adding additional capability.

In addition to the cost, power, and area coverage/microphone advantage of a distributed system, it is also fundamentally more robust than solitary array solutions. Additional sensors may be added to improve performance or coverage seamlessly, and some may fail without degrading the solutions significantly. Since inter-sensor data rates are small, and the signal processing burden is light, computation may easily be distributed to multiple sites, even to the individual soldier level, further enhancing the system's robustness.

These issues lead to the last three major components of our system concept:

7) Waterproof, low-bandwidth, cheap and simple sensors with integrated low-power electronics and processing. Mechanically undemanding arrays, and low-precision sensor orientations and locations which can be derived from COTS subsystems, including tape measures and levels.
8) Sensor distributions which are redundant (i.e. provide more than the minimum 6 shock travel times) so that some may fail without adversely affecting the solution.
9) Use of processing algorithms which easily accommodate more or less data on a shot by shot basis, and which automatically detect and eliminate poor quality or inconsistent data.

Again, the system concepts which support this goal are consistent with those derived from the previous goals.

2.4 System Concept Summary

The acoustic counter-sniper system concept is summarized in Figure 3. It shows:

- Low-cost distributed acoustic sensors of various types: omni, tetrahedral arrays, and helmet mounted arrays. These sensors may be in motion as long as supporting location and orientation data are provided.
- Wireless network communications among Sensor Nodes and Command Nodes. The two may be combined at one site, such as in a man-worn system. The network passes partially processed acoustic data and logistics support data, as well as solutions for the trajectory and sniper location. All of these are fundamentally low data rate.
- Use of the shock and optionally the muzzle blast to estimate the bullet trajectory and sniper location globally, using all available data integrated by an accurate ballistic and acoustic model.

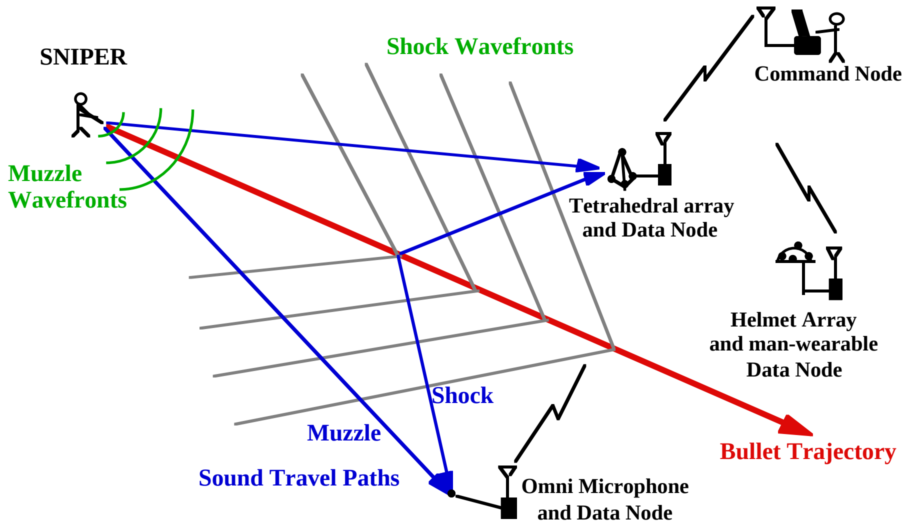

Figure 3. Distributed acoustic counter-sniper system concept.

3. SYSTEM ARCHITECTURE AND IMPLEMENTATION

Guided by the system concepts discussed above, a proof-of-principle (POP) system was constructed for live-fire testing directed by the government. The POP system described in detail and tested for this paper is small enough to be mobile and portable, but the sensors are fixed in location and orientation when in use. It was hardened and documented enough to allow five systems to be delivered to the government for further testing by operational personnel with minimal system training. This delivery was less than one year after the beginning of our initial POP development contract. We are currently developing and testing a POP man-wearable system with helmet-mounted sensors as described above. This system will have real-time differential GPS location and magnetometer-based orientation sensors allowing continuous helmet motion.

3.1 Hardware Architecture and Implementation

The POP system was developed primarily with commercial off-the-shelf (COTS) components and was designed with reconfigurability, incremental development, and ease of use in mind. Pictured in Figure 4, the system consists of Data Nodes which acquire time synchronized waveform data on up to 4 channels at 20 kHz each after detecting a shock wave, and a Command Node which receives the digitized data from up to 20 Data Nodes over a COTS FCC Pt. 15 wireless network using the Proxim RangeLAN II, which operates at 2.4 GHz. The Command Node archives and processes the data from all nodes, and displays the solution results.

3.1.1 Data Nodes

The Data Nodes are implemented using PC-104 format PC stack, including a 486 processor, 16 bit A/D converter board, GPS receiver, and PCMCIA interface to a 10 MB flash disk and the RF network system. Housed in a 0.1 cubic foot box along with the anti-alias filters, this forms a programmable data acquisition unit which continuously digitizes all channels, looks for shock events, captures up to 1 second of data, time-tags it to better than 10 μsec accuracy, and sends it over the RF network to the Command Node at an effective rate of 0.1 to 1 MB/sec, depending on range and antenna type. We have successfully used the systems in the field at 500 m RF ranges with better than 0.2 MB/sec data rates.

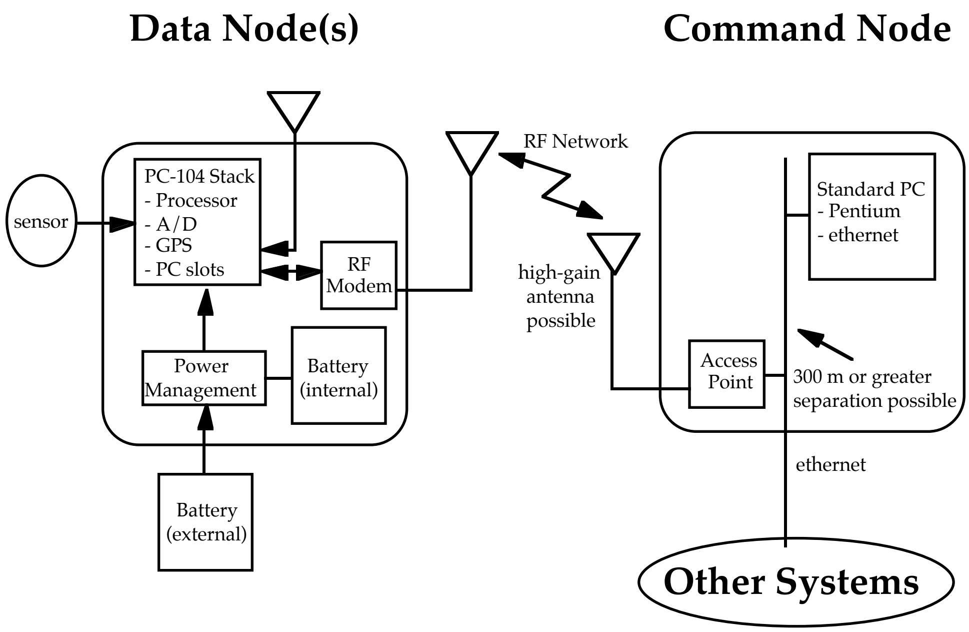

Figure 4. Proof-of-Principle (POP) System Hardware Configuration.

These small systems are compliantly packaged inside a 1 cubic foot weatherized and ruggedized shell which also houses a 12V Lead-acid gel-cell of 17 Ah capacity capable of powering the Data Node for approximately 17 hours. A power-management module allows external batteries to run and charge the system, and they may be replaced without disturbing system readiness. The Data Nodes have functioned successfully in direct sunlight at 95 degrees F and 95% humidity for an entire day's testing. A weatherproof multi-pin connector on the exterior of the shell connects it to up to four microphones, distributed or arrayed. The RF network antenna is internal to the shell, but the GPS antenna cable exits through a weatherproof bulkhead so that it can be co-located with a sensor. However, in this implementation, GPS is only used for time synchronization, and the inexpensive Trimble Svee6 unit used is not used with differential corrections adequate for sensor positioning use.

3.1.2 Command Node

The Command Node function can be run on any capable PC compatible running Windows 3.1 or Windows 95. We use a convenient lunchbox-style Pentium 160 MHz unit with PCI bus and color display, although a Laptop unit has been used successfully, and has the advantage of making the entire system battery powered. This is often useful in field tests. The wireless network hardware that can be used at this end of the system comes in three configurations. The first is a separate RF modem called an "Access Point" which connects to the Command Node via standard Ethernet. This configuration is shown in Figure 4, and has the advantage of allowing the modem to be placed far away from the Command Node (up to 1 km ethernet run). This also allows the user to have both choice of antenna gains (we use omni, 8 dB, and 12 dB gain directional antennas, depending on the Data Node distribution in the field) and keeps the lossy antenna runs short. The use of ethernet also allows results to be transmitted to other command and control systems. This was used in the government tests to archive our solutions in real-time. A unique feature of the Access Point solution is also that multiple units may be put on the ethernet and hand-off the Data Node communications in a cell-like fashion, depending on which has the best RF link. This allows a single command node to obtain data from a large field of potentially moving Data Nodes. The RF network modems are also available in standard ISA card format which fits inside the lunchbox style PC, and the PCMCIA format used in the Data Nodes which can be used with the Laptop. These make for more compact systems. However, the ISA cards allow external high gain antennas to be used, but do not allow very remote location of the antenna due to high cable losses at 2.4 GHz. The Laptop PC cards require no external power, allowing battery operation, but only offer a built-in omni antenna which is within 1 foot of the Command Node.

Although not exercised at the POP tests, three of the systems delivered to the government eliminated the RF data nodes and Command Node modems and used hardwired links from two tetrahedral arrays to a signal conditioning box which directly fed A/D converters in the Command Node computer. Software "Virtual Data Nodes" were implemented on this computer which functioned identically to the hardware Data Nodes described above, and had the same output interface. Otherwise, the functionality and use of these systems were identical to the RF systems.

3.1.3 Sensors

For our POP tests, we fielded two types of sensors in various configurations; distributed fields of 6 to 12 omni microphone sensors over 100 m aperture, and distributed fields of 2 to 3 four-element tetrahedral arrays with 1.5 meter inter-microphone spacing and 20-100 meter inter-tet spacing. Our 6 Data Nodes were capable of acquiring and transmitting data from all of these sensors simultaneously. The Command Node archived all raw waveform data and was variously configured to process all simultaneously, or just process subsets to determine the performance as a function of array configuration.

Because of the high pressure levels of a shock wave, very high dynamic range sensors are required. Peak pressures for a 50 caliber bullet within a few meters led us to set the maximum pressure capability at 145 dB re 20 μPa in the 0-8 kHz band to avoid clipping. Programmable gain settings could set this as high as 163 dB if required. For outdoor, weatherproof operation, Bendix AQ-4 hydrophones with local 30 dB preamplifiers were used for pressure transduction.

The tetrahedral arrays were of unique construction. A central weatherproof 0.05 cubic foot anodized aluminum hub housed the preamplifier and mounted to a tripod. The approximately 1 meter arms of the tetrahedron mounted to the hub via rigid weatherproof connectors. They were constructed of thin aluminum tubing which also serves as an electrostatic shield, and had the hydrophones mounted at the ends in a consistent orientation so that element directivity effects would not differentially influence the signals. Additionally, the resonances of the arms were damped and located far from the vortex shedding frequency for typical wind speeds. Care was taken to make them different for each arm to avoid mutual excitation of the entire structure. The small size and cross-section of the black and green hubs and arms also rendered them nearly invisible against both urban and natural backgrounds. They can be easily broken down and assembled without tools and are easily transportable. An integral level and site in the hub allows setup to the required accuracy without additional tools or instruments. Intra-array tolerances on the element locations of approximately 1 inch are easily achievable mechanically and are verifiable with a simple tape measure in the field. A cable of up to 0.5 km (typically 50 m) connected to the Data Node carried signal and power. Preamp power requirements are about 10 mW.

Although not part of the POP system, we have developed a helmet-mounted conformal acoustic array which will provide the same or better performance as the 1.5 meter tetrahedra. Full motion of this platform will be supported by GPS and head orientation sensors, allowing it to be integrated into global grid-referenced solutions with other sensor types.

3.2 Software Algorithms, Architecture, and Implementation

The software developed for the POP system emphasized modularity, ease of insertion of new algorithms and data types, and ease of access to intermediate processing results and data products. It was written in C, C++, and Matlab. In particular, it used a Matlab GUI for operator input and text and graphical/image display and for all signal processing. It was not written for processing speed, although it computes a solution in less than 30 seconds for large numbers of sensors, and in less than 15 seconds for two tetrahedral systems. We expect that a purely C/C++ coded version would reduce this time to three to five seconds on the same Pentium processor.

3.2.1 Algorithms

A block diagram for the major processing steps is shown in Figure 5. Acoustic data is continuously digitized by the Data Nodes and a single channel for each sensor is scanned for a shock wave arrival using either a fixed pressure threshold, or a CFAR (constant false alarm rate) background noise normalizer and threshold detector in the *initial shock detection* module. In practice, both methods have functioned equally well because of the high SNR of the shock wave, though the normalizer is more robust in noisy situations. When an initial shock detection is made, the Data Nodes grab a *waveform snippet* from the A/D ring buffers of specified length and pretrigger duration (to account for sensor aperture). This is transmitted to the Command Node software over the network along with the absolute time of the snippet's first sample.

The Command Node software first detects the shock wave leading edge on all channels in the *shock edge detect and classify* module. It does this by high-pass filtering the data above 700 Hz and running another CFAR detector. These *absolute arrival times* are stored, and a smaller *shock waveform* consisting of just the N-wave is passed to the *shock wave cross-correlator* for precise relative time of arrival estimation. This is done only for inter-element processing on array sensors (e.g. tetrahedra and helmets) in which the added accuracy of the cross-correlator is required because of the small inter-microphone baselines, and makes sense because the N-waves on all microphones are similar because their slant ranges are nearly identical. These *relative arrival times* are also stored.

Next exercised is the *analyze waveform characteristics* module which estimates slant range from the N-wave by two different methods, each of which depend on bullet caliber. The caliber for the slant range pair which agree most closely is used as the *caliber estimate*, and the corresponding slant range is used as the slant range estimate. The caliber is the primary correlate of bullet *ballistic coefficient.*

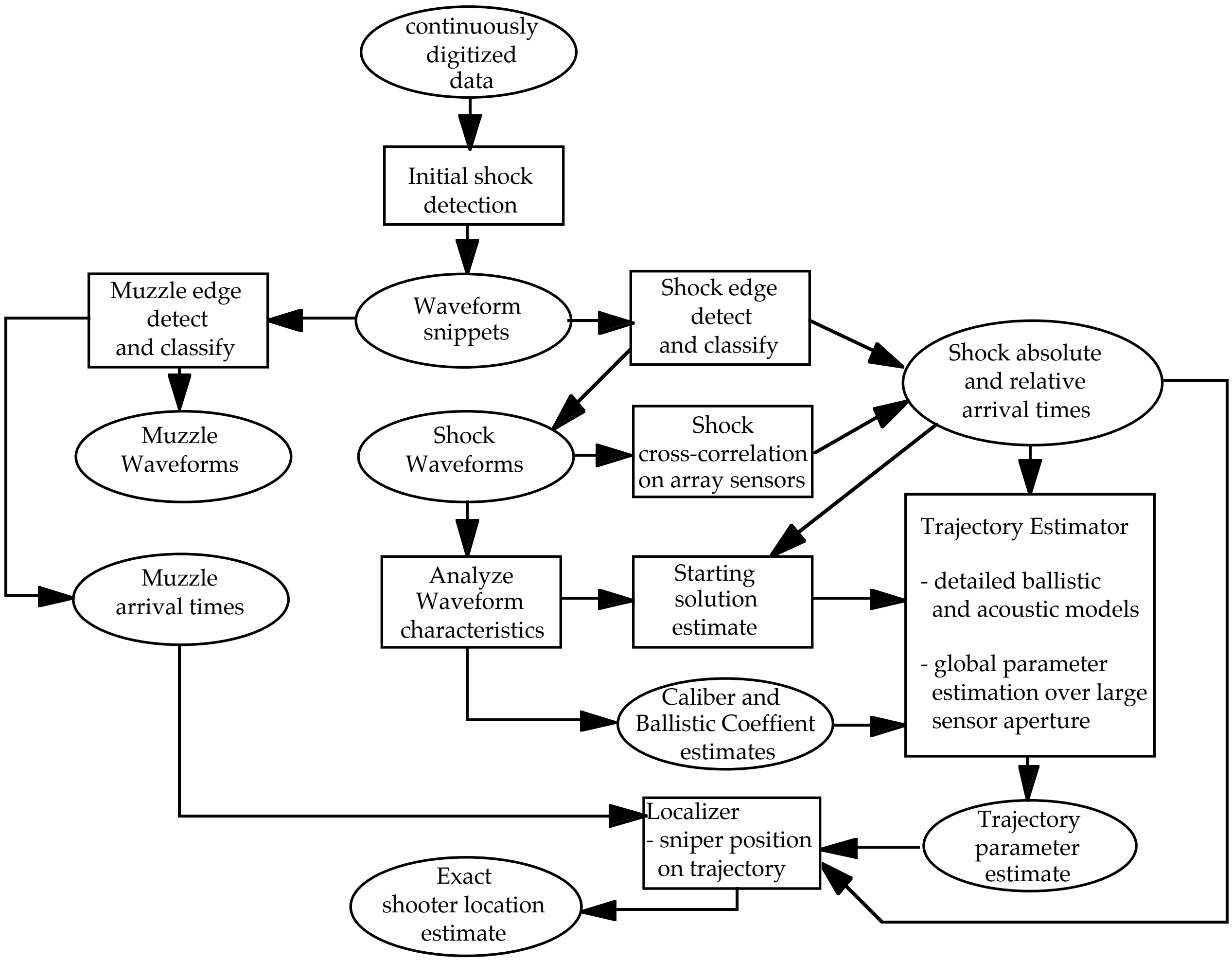

Figure 5. Proof-of-Principle (POP) System Processing Block Diagram.

The *starting solution estimate* module is fed by the *shock relative arrival times*, and the slant range to form an initial coarse estimate of the trajectory using simple trigonometry and/or a coarse grid search of the solution space for a non-decelerating bullet for the best fit. The simplified ballistics model is used to speed up the calculations, which are much simpler for a constant speed bullet. This *starting solution estimate* is passed on to the *trajectory estimator* module.

The *trajectory estimator* module uses the *ballistic coefficient* and detailed decelerating projectile ballistic model and acoustic time of arrival (TOA) model in a non-linear optimization to estimate the five parameters of the bullet trajectory from the observed *absolute and relative times of arrival*. These parameters are shown in Figure 6, along with absolute time, t_0, and the sniper location, (x_0,y_0,z_0). The non-linear optimization uses the iteratively-reweighted nonlinear least squares algorithm[1] to globally estimate the trajectory over all the available data after initialization with the *starting solution estimate*. This procedure optimizes the least absolute value (L1) error criterion rather than the least squares (L2) error. This error criterion is extremely robust to the presence of poor quality data with large potential outlier values mixed in with good data. We have found that most practical data acquisition scenarios from multiple sensor sites contain these types of errors due to global detection errors and sensor mislocations and misorientations which can only be recognized in the context of the final correct solution. L1-based algorithms automatically do this, and do not require laborious and error-prone rule-based data editing. The final output product of this module is the entire bullet trajectory, in the form of the five-member *trajectory parameter estimate.*

As stated in section 1, the trajectory estimate from the shock wave alone can provide a reasonable prediction of the shooter location if digital maps are available to trace the trajectory back to obstructions or likely shooter locations. Since we use a decelerating bullet model, the trajectory can also be traced back to the point where the bullet speed is the known muzzle velocity of likely weapons being used.

However, in many circumstances the muzzle blast wave may be available, in which case our algorithms exploit it to provide a better estimate of the shooter 3-space location which does not depend on this type of prior information. The *muzzle edge detection and classification* module filters the *waveform snippet* to a band from approximately 100 to 500 Hz optimized for the muzzle blast from various weapons. A CFAR detector with parameters optimized for the muzzle blast characteristics looks for the leading edge of the blast on each microphone channel. Because these detections are made in the presence of reverberation and scattering of the shock wave from nearby buildings and topography, many false detections may be made. For this reason, a classifier is run which compares the energy above 700 Hz to that below 500 Hz for each of the detections. If this ratio exceeds a certain value (obtained from many datasets), it is called a false detection, and is eliminated. If any detections on any channel are not eliminated in this manner they are output as *muzzle absolute arrival time* data. These data, the *shock absolute arrival times*, and the *trajectory parameter estimate* are combined in the *localizer* module which estimates the sniper location on the trajectory. This is a single parameter estimator which uses the same L1 procedure as the *trajectory estimator* to obtain a robust estimate of the *exact shooter location*. This estimator again weeds out globally wrong data, and uses the predominance of the evidence to obtain what is effectively the range estimate to the shooter along the trajectory.

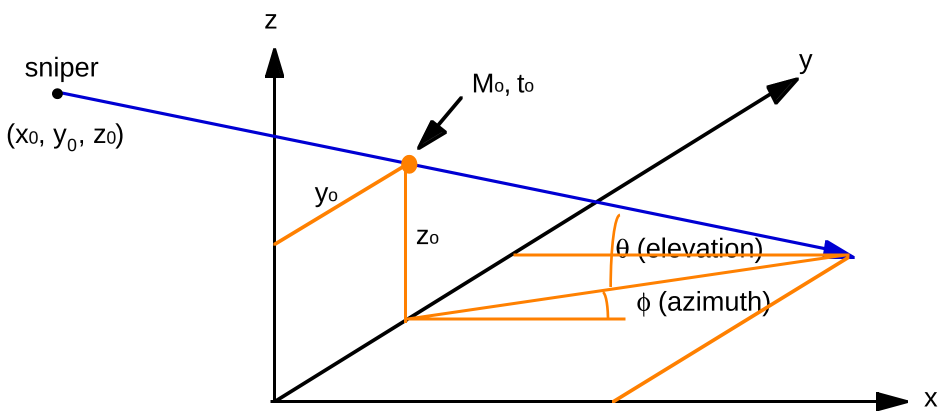

Figure 6. Estimated Trajectory and Sniper Location Parameters.

3.2.2 Software Architecture and Implementation

The software architecture is modular, and draws very clean interfaces between the various modules described in the previous section. The major system components and their locations and interfaces are shown in Figure 7. Upon power-up the Data Nodes boot using code resident on their flash disks, then get the latest application program from the Command Node. Once running, the data are digitized, initial shock detected, and snippetized on the Data Node and are shipped across the RF network using Network File Sharing (NFS) to the Command node. Using this mechanism, raw data are always written and stored on the Command Node at the operating system level, regardless of the state of the Command Node counter-sniper application code. No data is ever lost as long as the computer is running and the communications link is up.

On the Command Node, the user configures the system using a GUI which writes disk and memory resident control parameter structures which the various modules read. The primary real-time module is the *Data Association and Real-Time Scheduler*. This looks for incoming data from the Data Nodes by checking *detection flag* files. It associates likely events using the file time tags, and constructs *event lists* which the *detect and classify* module uses to decide which *waveform snippets* to process together as a likely shot event. The output of this module is the *arrival time* and other waveform derived parameters which are used by the *trajectory estimator and localizer module* to obtain the *trajectory parameters and shooter location.* Finally, a *display module* provides both text and graphical output displays of intermediate data products, including raw snippet data, and bullet trajectories and shooter locations overlaid and justified to digital maps and grid coordinates. This display also provides different perspectives to view elevations as well as plan views. A helpful feature in the GUI used for configuring the system and setting system parameters is an intelligent "guide" that highlights the next logical dialog box, button, or entry to be modified or verified. This guides the user through setup and vastly decreases user errors. Another useful feature is a RF link status panel which alerts the operator to malfunctioning communication links. This is tested every 30 seconds by transmitting a Data Node status file. Because the raw data are all archived, they may be reprocessed by the system in a playback mode to test algorithm and parameter changes.

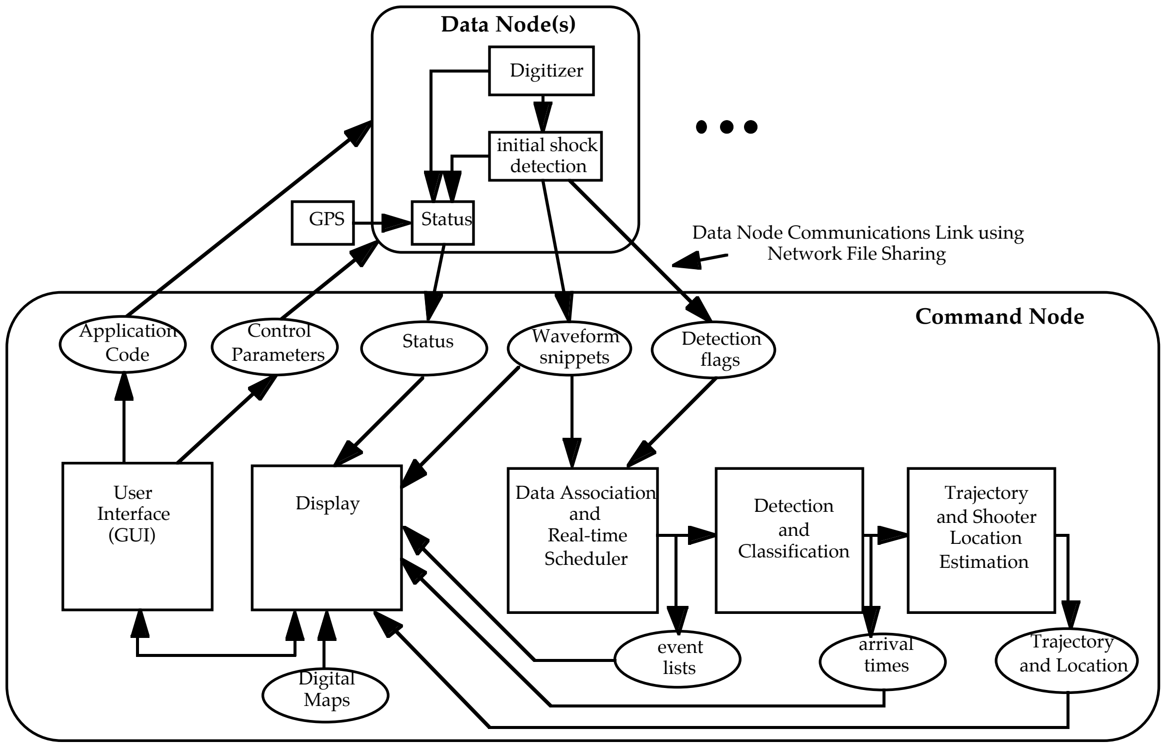

Figure 7. Proof-of-Principle (POP) System Software Architecture.

For the POP system, all code in the Data Node was written in C and 486 assembler, and runs under the DOS operating system. All code on the Command Node was written in C++ or Matlab, and runs under Windows 3.1 or Windows 95. We used the Netware Lite networking package to communicate between the two node types. For the man-wearable POP system being developed at this time, the architecture is similar, but much more of the processing will be moved to the Data Node which will be low power and resident in the helmet. Specifically, all the detection and classification for the local sensor will be done there. This will reduce the data rate out of the helmet over its RF link to reduce the total time-late of the solution.

4. BALLISTIC AND SHOCK WAVE ACOUSTIC MODEL

The primary enabling technologies for the acoustic counter-sniper system using distributed sensors are:

- An accurate ballistics and shock-wave acoustics model accounting for bullet deceleration.
- An accurate and robust method for estimating bullet caliber, and hence ballistic coefficient from the shock wave.
- The use of a robust global trajectory parameter estimation algorithm with the ballistics and shock-wave acoustics model embedded in it.

We have discussed the latter two points in previous sections. In this section we will discuss some of the details of our ballistic and shock-wave acoustic model.

The mathematical model that predicts the arrival time of a shock wave at any general point in space as a function of the full set of parameters is called the TOA model. We derived, from physical principles, a precise ballistic model that has an accuracy of approximately 10 parts per million (ppm). Existing ballistic models, all empirically derived, have nominal 1 m accuracy at 1 km, or 1000 ppm.

The use of the TOA model is illustrated in Figure 8. The 30 caliber bullet trajectory is coincident with the abscissa, and it is fired at zero time from the origin at Mach 2.7. The locus of the shock wave, in the plane of the trajectory, is shown at four successive times (0.5, 1.0, 1.5, 2.0) seconds. Microphones represented by the four black circles receive the shock wave at the four successive plotted times. The two microphones represented by white circles to the right receive the shock wave at different times, while the microphone on the left never receives a shock wave, because it is in a shadow zone. The loci become increasingly more curved as time progresses, due to the slowing down of the bullet because of the drag force acting upon it. It is this slowing down of the bullet that must be predicted accurately by the ballistic model.

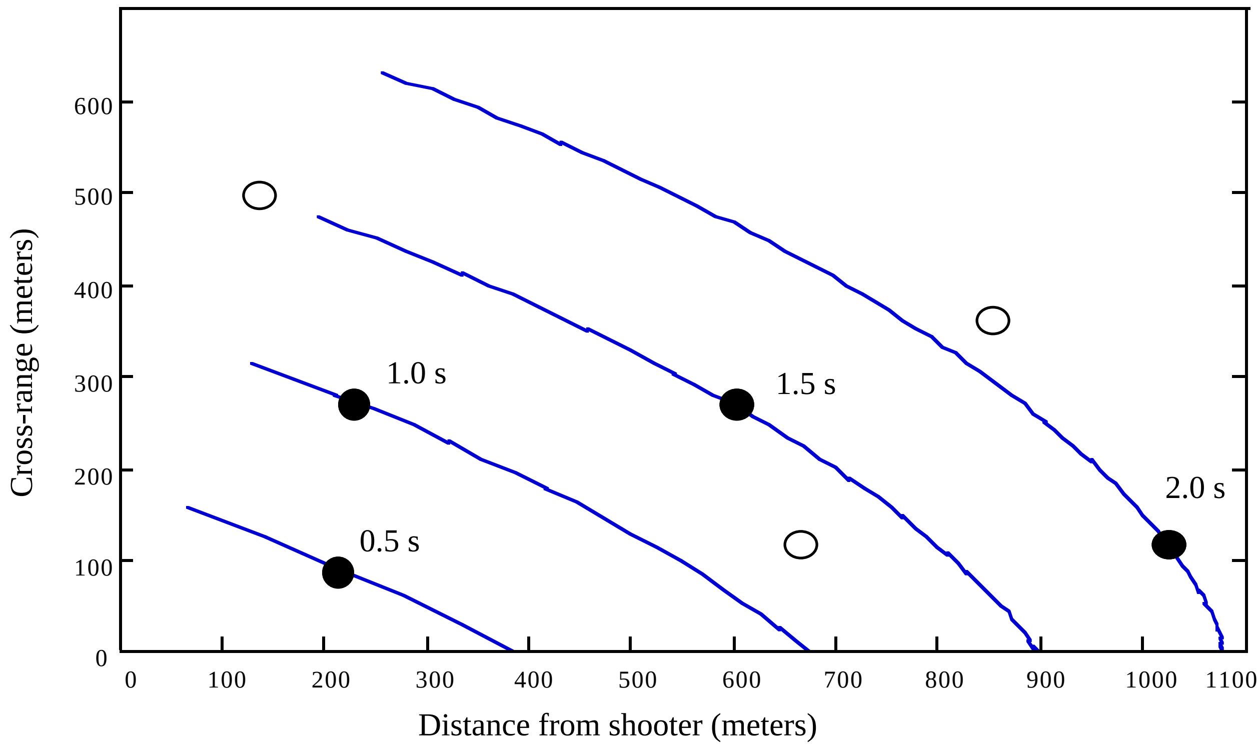

Figure 8. Wavefront locus of TOA model at four observation times.

The development of the ballistics model is sketched in the following manner. The drag force, F, is represented in the conventional way using a drag coefficient C_d, and this force acts to decelerate the bullet having mass m, hence

$$F = 1/2\ \rho\ A\ V^2\ C_d = -\ m\ dV/dt.$$

It is known that the drag force for supersonic bullets is much greater than for subsonic ones, so that we postulate that the sound radiation (the shock wave) dominates the drag. By equating the rate of sound power radiated to the loss of kinetic energy, the drag coefficient is found to be given by a remarkably simple relationship involving the bullet radius R_o and its Witham function, $F(\xi)$, which is a function of the entire shape profile of the bullet[2].

$$Cd = (2/Ro^2)\ \int\ F(\xi)^2\ d\xi$$

$$F(\xi) = 1/2\pi\ \int\ (2/\alpha R(u))^{1/2}\ H((\xi-u)\ /\ \alpha R(u))\ d(A(u)/du), \quad \alpha = (M^2-1)^{1/2}$$

By carrying out the indicated Reimann-Stieltjes integral, over the range of Mach number extending from 1.1 to 3.0, we find that the drag coefficient is given by the simple relationship $C_d = \kappa\, M^{-0.514}$, where κ is a different constant for each caliber bullet. Popular empirical ballistics models are based on drag coefficients having similar relationships, but use a value of -0.5 for the Mach number exponent.

The development of the TOA model from the ballistics model is shown in Figure 9. The time of arrival is equal to the time it takes for the bullet to get to the point were sound is radiated from it toward the microphone, plus the time that it takes the shock wave to get from its radiation point to the microphone.

$$t = t(x) + s/c, \quad \text{where } x = x0 - r(M^2-1)^{-1/2}.$$

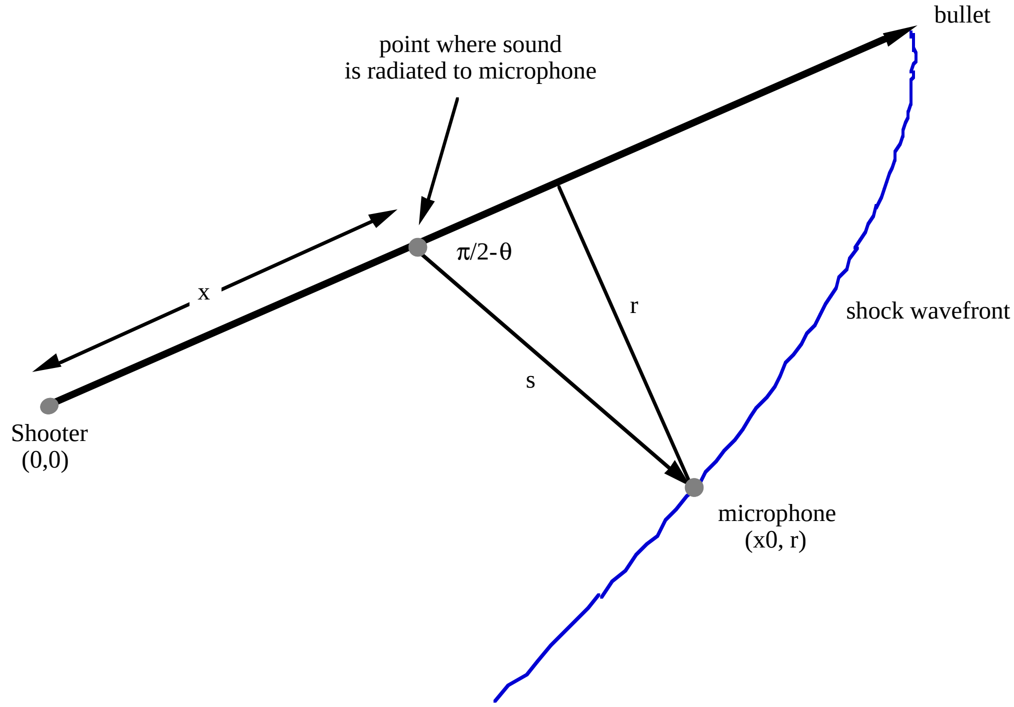

Figure 9. Shock-wave Time of Arrival (TOA) Model.

The ballistics model gives the first of these two times, and is given by:

$$t(x) = C_b/2(1-n)\ [(V_o^{n} - 2nx/C_b)^{(n-1)/n} - V_o^{n-1}] + r/c\ (1-M^{-2})^{-1/2}$$

where

$$M = 1/c\ (V_o^{n} - 2nx/C_b)^{1/n}$$

and

$$C_b = 4m/\kappa\rho A c^{n}$$

where n = 0.514 is the constant derived above. The second time is simply the distance s, divided by the speed of sound, c. The distance s is related to the closest point of arrival (CPA) distance, r, by $r = s\cos(\theta)$, where θ is the Mach angle, and where $\sin(\theta) = 1/M$.

5. SYSTEM DEMONSTRATION AND PERFORMANCE

5.1 Background

The acoustic counter-sniper system was demonstrated in three government sponsored and directed tests at Camp Pendleton[3] in the spring of 1996. These included both distributed omni and tetrahedral array deployments in an open firing range area and a simulated urban environment called the Mobile Operations, Urban Terrain (MOUT) facility. Several hundred shots were fired during these tests from several shooter positions to several target locations. Different types of rifles with various muzzle speeds were used, and included 22, 30, and 50 caliber rounds. The trajectories were designed to exercise different potential performance problems. Although our system was designed for, and achieves its best performance with a large distributed array of sensors, most testing was done on a two-tetrahedral array configuration with a 40 m separation. This configuration uses only 8 microphones and two data nodes. This configuration was chosen because it was consistent with the sensor configurations of other systems being tested at the same time. We report only the results of that test here.

5.2 System Deployment and Test Procedure

The two-tetrahedral system was set up in the town-square area of the MOUT facility. The arrays were deployed 1.5 meters above the sidewalk pavement, and within 10 to 20 meters of substantial 2 to 5 story concrete block buildings. Other acoustic obstructions and scatterers, such as burned out vehicles were also near the arrays. The array location points on the sidewalk were provided by the government from a commercial GPS survey. We set up the tetrahedra and leveled them using their built-in bubble levels to approximately 0.2 degrees resolution. The arrays were oriented using their built-in sites to aim a particular arm on each at the other array. This procedure is documented in a complete user's manual, which walks the user through entry of the setup data into the appropriate tables in the GUI. The entire setup procedure takes about 30 minutes. It should also be noted that if justification to a map grid is not needed, all surveying of the relative array locations could have been done with a tape measure (on level ground). A transit level can be used if there is significant topography. From these data, one can define their own local coordinate system.

The data were transmitted from the Data Nodes in the town square to the Command Node antenna on a building approximately 100 m away. Direct line of site to one of the nodes was through a group of the concrete block buildings, but the RF link still functioned well.

5.3 System Performance

The data taken during the last test using only two tetrahedral arrays were processed using the software delivered to the government with the five systems to be tested. The result of this processing on the 167 shots from day two of the test is as follows:

- 90% of the total shots were detected by the system
- On these the following performance was obtained:

Caliber: 90% had were estimated correctly

Azimuth:	72% had errors less than 1 degree 93% had errors less than 5 degrees 96% had errors less than 10 degrees.
Elevation:	38% had errors less than 1 degree 91% had errors less than 5 degrees
Range:	28% had errors less than 1% 60% had errors less than 5% 70% had errors less than 10%

These correspond to 1.2 degrees rms for the azimuth and 3.0 degrees rms for the elevation errors. This performance was obtained with the weakest sensor configuration that the current POP system can handle, two tetrahedra. An additional tetrahedron, or even one or more omni sensors would significantly increase the performance of the system. We also believe that most of these errors were due to sensor orientation and position errors, with perhaps some component due to unmodeled propagation phenomena, such as wind and temperature variation. Supporting this conclusion, the Cramer-Rao lower bound predicted for this configuration with our estimated detection time errors is 2 to 5 times lower than the results obtained, depending on the geometry. This value is consistent with the standard deviation of any single group of shots along the same trajectory line.

An example of this is shown in Figure 10. There are approximately 20 shots on two trajectories in this figure. They overlay very tightly (approx. 0.2 degrees rms), and show a small bias from the correct value of approximately 0.4 degrees. We believe that it is the differing bias terms from each shot geometry that contribute a significant component of the observed error. These may be reduced by more careful installation. Figure 10 also illustrates the resolving capabilities of the system, and its potential operational utility. The two shooter locations are in windows at either end of a building. These were clearly delineated in both range and angle.

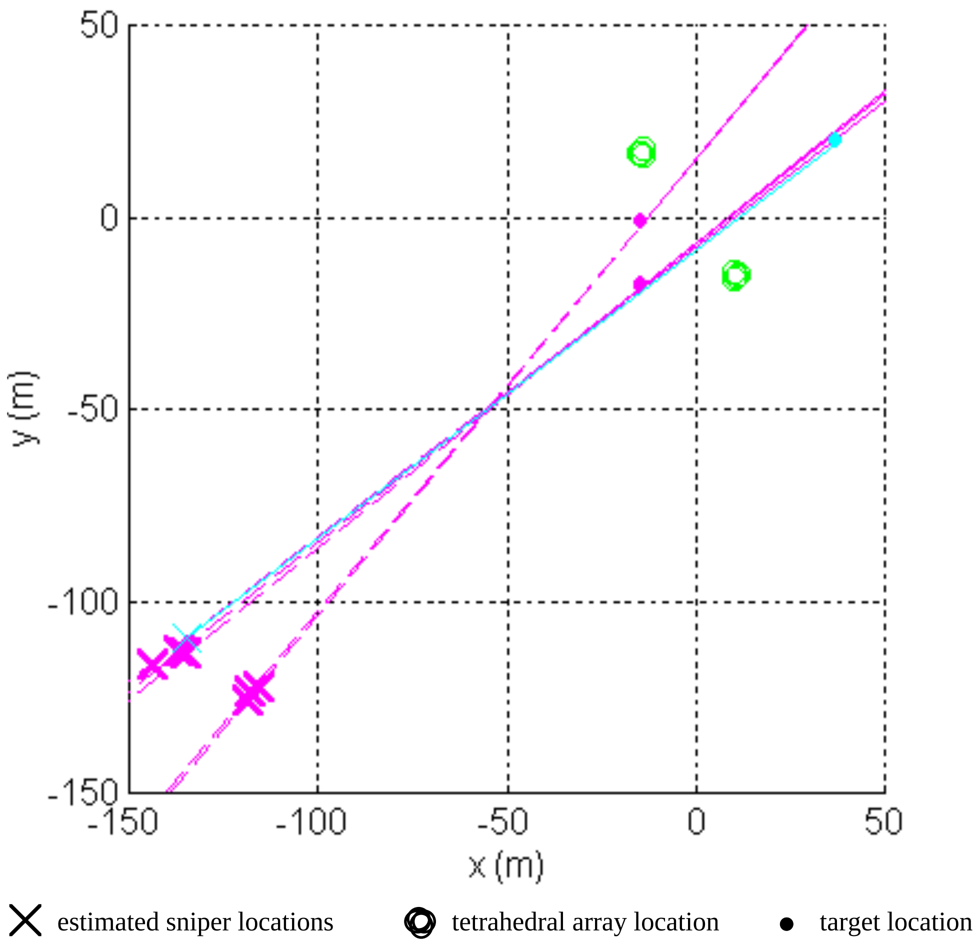

Figure 10. Shot trajectories and sniper location estimates for two shooter locations and two targets.

ACKNOWLEDGMENTS

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